Soil Background Effects on Reflectance-Based Crop Coefficients for Corn*

Walter C. Bausch[†]

A previously developed reflectance-based crop coefficient (K_{cr}) for corn, estimated from the normalized difference vegetation index (NDVI), has been shown to overestimate the basal crop coefficient (K_{cb}) for corn by 24% or more when used with a dark-colored soil. This overestimation occurs because the NDVI produces larger index values for the same vegetation amount over dark backgrounds. Thus, the purpose of this article was to investigate newer vegetation indices that have been developed to minimize soil background effects and to develop a reflectance-based crop coefficient for corn that applies over a wide range of agricultural soil reflectance. Two soils (light- and dark-colored) with red reflectance of 31% and 13%, respectively, were selected for this study. Reflectance data of the corn canopy were acquired with four combinations of these soils (light, dry; light, wet; dark, dry; and dark, wet) in trays inserted at the same place beneath the corn canopy. The soil adjusted vegetation index (SAVI), with an adjustment factor (L) set to 0.5, was found to adequately minimize soil background influences from sparse to dense vegetation conditions. A linear transformation between the K_{cb} for corn and the SAVI was used to convert the SAVI into the K_{cr}. The maximum difference for this K_{cr} between the light, dry soil background and the dark, wet soil background (extreme cases) was less than 6%. The K_{cr} based on the SAVI corrects for a wet soil surface and requires no additional calibration to estimate the basal crop coefficient for corn grown on most agricultural soils.

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INTRODUCTION

Calculated reference crop evapotranspiration and crop coefficients provide a practical and an inexpensive method for estimating actual crop evapotranspiration (E_t) throughout a growing season. Crop coefficients are expressed as a ratio of the E_t of the crop under consideration to the E_t of the reference crop, that is, alfalfa or grass. They have a minimum value following planting which represents bare soil conditions, approach 1 or become greater than 1 at effective cover depending on whether the reference is alfalfa or grass, respectively, and then decrease in magnitude as the crop matures. Effective cover for E_t of agricultural crops has been considered to occur around a leaf area index (LAI) of 3 and/or 75% ground cover (Stegman et al., 1980).

van Wijk and deVries (1954) proposed the concept of crop coefficients for estimating E_t of field crops, which was later developed by Jensen (1968). Initially, crop coefficients represented an average condition in the field between a wet and a dry soil surface without soil water limitations in the crop root zone. These crop coefficients were referred to as mean crop coefficients (K_{co}). Wright (1982) introduced basal crop coefficients (K_{cb}) in which the soil evaporation component of E_t is minimal due to a dry soil surface; however, available moisture in the crop root zone is adequate such that transpiration is not limited.

Published basal crop coefficients for specific crops represent average plant growth conditions for the specific growing seasons used in their development. Various factors (weather anomalies, nutrient deficiencies, insect damage, disease, stress, etc.) cause plant growth to deviate; consequently, crop E_t may be different than estimated by using published crop coefficients.

Jackson et al. (1980) showed similarities between the K_{co} for small grain and the ratio of the perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977) of wheat to the PVI of wheat at full canopy cover. Heilman et al. (1982) developed relationships between the K_{co} for alfalfa and percent canopy cover and between the PVI and percent canopy cover to infer the K_{co} for alfalfa from spectral estimates of canopy cover.

Neale and Bausch (1983) and Bausch and Neale (1987) outlined the potential for developing crop coefficients from reflected canopy radiation by relating agronomic variables that effect E_t with spectral data obtained over plant canopies. They showed that the seasonal curve of the normalized difference vegetation index (NDVI), described by Deering (1978), for corn was similar to its K_{cb} curve calculated from Wright's (1982) data. A linear transformation between the NDVI and the K_{cb} was proposed to represent the reflectance-based crop coefficient (K_{cr}). The K_{cr} was obtained through linear scaling by setting the average NDVI of dry, tilled bare soil for the site equal to the K_{cb} value for dry, bare soil (0.15) and setting the average maximum NDVI value for the site equal to the K_{cb} value for effective cover (0.93). Its mathematical representation is

$$K_{cr} = a \times \mathrm{NDVI} + b, \tag{1}$$

where a is the multiplier and b is an offset. The multiplier is a ratio of the difference between the K_{cb} for effective cover and bare soil to the difference between the NDVI for effective cover and bare soil. The offset represents the difference between the K_{cb} and the multiplier times NDVI at either the bare soil condition or the effective cover condition to make K_{cr} equal 0.15 for bare soil or K_{cr} equal 0.93 for effective cover, respectively. This transformation directly relates the NDVI with Wright's (1982) basal crop coefficients by forcing it through two points on the K_{cb} curve. Thus, the K_{cr} is an instantaneous representation of the basal crop coefficient calculated from canopy reflectance data.

Neale et al. (1989) concurrently measured reflected canopy radiation and E_t of corn with weighing lysimeters to compare the reflectance-based crop coefficient (K_{cr}) for corn with the calculated K_{cb} for corn. They showed that the NDVI which was used to calculate the K_{cr} reached its asymptote at a LAI of approximately three and 80% ground cover which is when effective cover occurs for most agricultural crops. Also, the date of effective cover obtained from the K_{cb} data occurred within 4 days of the date on which the NDVI curve reached its maxima. Neale et al. (1989) presented two equations for the reflectance-based crop coefficient for two research sites (Fruita and Greely, CO):

$$K_{cr} = 1.092 \times \mathrm{NDVI} - 0.053 \tag{2}$$

and

$$K_{cr} = 1.181 \times \mathrm{NDVI} - 0.026, \tag{3}$$

repectively. Differences between the two equations were essentially due to soil reflectance at the two locations. These equations apply throughout the growing season and mimic the growing season K_{cb} curve. The K_{cr} defined in Eqs. (2) and (3) is independent of the traditional time base parameters (planting date and effective cover date) associated with published basal crop coefficients. Since NDVI is a measure of the photosynthetic size of the crop canopy (Wiegand et al., 1991), the K_{cr} is responsive to anomalous plant growth induced by weather conditions as well as to leaf loss due to hail and foliar stresses caused by insects, disease, and water deficit. Consequently, the K_{cr} represents actual field conditions.

Bausch and Neale (1989) and Bausch (1989) demonstrated use of Eq. (3) in irrigation scheduling. When the reflectance-based crop coefficient was compared with the traditional crop coefficient for irrigation scheduling, there were differences of 1–3 days in simulated irrigation dates (Bausch and Neal, 1989). One less irrigation was required for the field utilizing the reflectance-based crop coefficient than the traditional one (Bausch, 1989). Crop development during the growing season for the test year, 1988, was normal with no disturbances to plant biomass; consequently, one would not have expected any differences that could be attributed to the traditional crop coefficients.

Elvidge and Lyon (1985) and Huete et al. (1985) showed that the NDVI for incomplete vegetation cover produced larger vegetation index values for dark- than for light-colored soils. A sensitivity analysis of the NDVI for a range of soil background reflectances by Neale (1987) using the Suits (1983) canopy reflectance model agreed with those results. Use of the NDVI to estimate the crop coefficient contained the soil background influence; thus, the reflectance-based crop coefficient differed by 24% between simulated results for a lighter-colored soil and the darkest soil and 7% between this light soil and an even lighter soil. Consequently, the crop coefficient based on the NDVI overpredicts the basal crop coefficient for dark soils and, thus, crop E_t. The objective of this article was to investigate indices that are less influenced by soil brightness and to select an index that can be used for a reflectance-based crop coefficient over a wide range of soil background reflectances.

METHODS

Experimental data were collected at the Agricultural Engineering Research Center (40.595°N lat., 105.137°W long.) at Colorado State University during the 1991 growing season. Two field plots approximately 45 m × 45 m were planted to corn (*Zea mays* L.) cultivar "Pioneer 3732" on day of year (DOY) 122 (2 May). Row direction was north / south and row spacing was 0.76 m. Plant population was 7.5 plants / m^2. The plots were irrigated with a small two-tower center pivot sprinkler. A small area was set up in the north plot so that trays of soil could be placed under the corn canopy to change the soil background in the target area viewed by a radiometer.

Two soils were used in this study. The soil was sieved through 10 mm square mesh screen to remove clods and foreign matter, uniformly mixed, and placed in four sets of trays. One set for each soil was kept dry throughout the measurement period; the other set of trays for each soil was uniformly sprinkled just prior to each measurement sequence on that particular day. One soil tray from each of the four soil backgrounds was designated for soil reflectance measurements. Munsell color notations were: 10YR6 / 3 for the light, dry soil; 10YR4 / 3 for the light, wet soil; 10YR3 / 3 for the dark, dry soil; and 10YR3 / 1 for the dark, wet soil.

The target location consisted of a single area 2.28 m wide (four rows or three row spaces) by 2.4 m in length. Six trays (0.76 m wide by 1.22 m long by 2 cm deep) were used for each of the four soil conditions. Two trays were placed end to end on each of three carts that were pushed into the target area to cover the space between four adjacent rows. These carts rolled on inverted angle iron tracks such that the tops of the soil trays were approximately 6 cm above the soil surface. The width of the trays was decreased as needed as the crop grew (stalk diameter increased) to prevent damage to plants in the target area by the sides of the trays.

Data acquisition on any particular measurement day bracketed solar noon and consisted of measuring soil radiance over the designated soil trays which were placed on a stand (one at a time) to keep them above the corn canopy, then measurements of canopy radiance with the various soil backgrounds alternately inserted beneath the corn canopy, and finally soil reflectance measurements again. Each measurement sequence started and ended with the radiometer optics covered to measure voltage noise on each of the four channels. The wavebands used in the radiometers were 0.45–0.42 μm (blue), 0.52–0.60 μm (green), 0.63–0.69 μm (red), and 0.76–0.90 μm (near-infrared). These wavebands are similar to Landsat Thematic Mapper Bands TM1, TM2, TM3, and TM4, respectively.

Light reflected by the target was measured with an Exotech[1] model 100BX four-channel radiometer fitted with 15° circular field of view (FOV) optics. Incoming light was measured at the same instant in time with another Exotech radiometer fitted with 2π steradian FOV optics. The down-looking radiometer was pointed perpendicular to the surface of the target, that is, a nadir view angle. It was positioned 1 m above the center of the soil trays for measuring soil radiance and 5.8 m above the target area for canopy radiance measurements. The down-looking radiometer viewed a spot 1.5 m in diameter centered in the canopy target area. The up-looking radiometer was positioned approximately 3.5 m above ground on a nearby mast and leveled in the horizontal plane. An Omnidata Polycorder (Model 516B) sampled voltages from the radiometers and logged the data.

Reflectance data were acquired on 12 clear days between DOY 137 (17 May) and DOY 219 (7 August) (Table 1). Average sun angles (zenith and azimuth) during the 15-min period for canopy background measurements over the target area are also presented in Table 1. Mean reflectance and standard errors for the two soils in wet and dry conditions are given in Table 2.

Bidirectional reflectance of the target was calculated for each of the four wavebands using a procedure similar to that presented by Duggin (1980), as described by Neale (1987). The $BaSO_4$ reference panel used for intercalibration of the radiometers was calibrated on 22 May 1991 at the USDA-ARS, U.S. Water Conservation Laboratory, Phoenix, Arizona (33.433°N lat., 112.017°W long.) by Jackson using procedures developed by Jackson et al. (1987) and slightly modified by Jackson et al. (1992). Intercalibration of the up- and down-looking radiometers was also performed that same day.

Leaf area was measured at least twice each week. From the first to fourth leaf growth stage [V1–V4 (Ritchie et al., 1986)], four average-sized plants were harvested from the border area surrounding the target area and taken into the laboratory for leaf area determination with a Li-Cor LI-3100 area meter. Starting with the V5 growth stage a LI-3000A portable area meter was used. Leaf area index (LAI) was calculated based on the plant population.

Table 1. Measurement Dates, Sun Angles, Growth Stage, and LAI of Corn

DOY	*Sun Angle (°)* *Zenith*	*Azimuth*	*Growth Stage*	*LAI*
137	21.4	177.9	VE	
149	19.0	179.5	V2	0.02
162	17.6	178.0	V4	0.10
171	17.2	178.4	V7	0.31
176	17.3	179.8	V8	0.58
182	17.6	182.7	V9	1.16
184	17.6	179.6	V10	1.43
191	18.5	175.3	V12	2.58
196	19.2	175.6	V14	3.33
198	19.5	176.0	V15	3.55
210	22.0	176.9	R1	4.10
219	24.2	181.0	R2	4.16

[1] Brand names are given for the benefit of the reader. They do not imply endorsement by the author or USDA-ARS to the exclusion of similar products available from other vendors.

Table 2. Soil Reflectance[a] for the Two Soils Maintained in a Dry and Wet State

Soil Description	TM1 (0.45–0.52 μm)		TM2 (0.52–0.60 μm)		TM3 (0.63–0.69 μm)		TM4 (0.76–0.90 μm)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Light, dry	0.1672	0.0055	0.2411	0.0064	0.3098	0.0057	0.3820	0.0059
Light, wet	0.0832	0.0038	0.1332	0.0045	0.1853	0.0064	0.2454	0.0073
Dark, dry	0.0729	0.0021	0.0991	0.0025	0.1276	0.0026	0.1841	0.0031
Dark, wet	0.0445	0.0031	0.0593	0.0038	0.0764	0.0047	0.1181	0.0059

[a] Means and standard errors were calculated from reflectances for the 12 measurement dates.

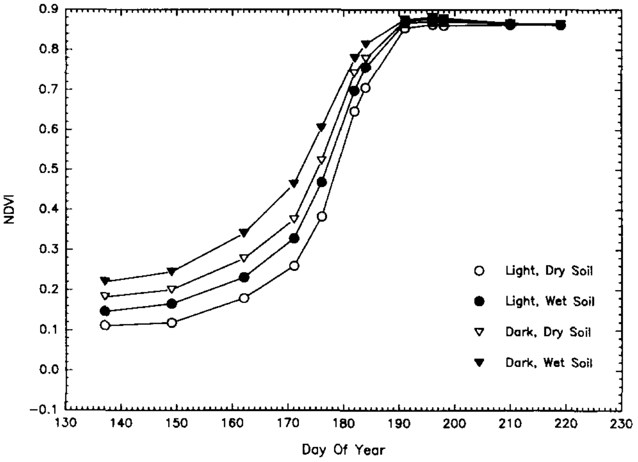


Figure 1. Soil background effects on the normalized difference vegetation index (NDVI) throughout the vegetative growth period of corn.

RESULTS AND DISCUSSION

Corn growth stage and LAI as predicted by a best-fit curve through the LAI versus DOY data for the 12 reflectance measurement dates are given in Table 1. Corn emergence (VE) occurred on DOY 136; corn was at VT (tassel stage) on DOY 207. On DOY 220, a hail storm shredded the upper leaves. Reflectance data acquired on DOY 137 represented bare soil because the soil tray surfaces were above the small corn plants and the tray edges touched.

The reflectance-based crop coefficient developed by Neale et al. (1989) was based on the NDVI because that index is widely used and is robust across illumination conditions. However, the NDVI was found to be very sensitive to the optical properties of the soil background at incomplete vegetative cover conditions (Fig. 1) as previously shown by Elvidge and Lyon (1985) and Huete et al. (1985). The NDVI was essentially the same for all soil backgrounds on DOY 193 which corresponds to a LAI of approximately three (Table 1).

Table 3 gives the NDVI for each soil background for bare soil and for effective cover. The multiplier and offset for the K_{cr} equation [Eq. (1)] for each soil background are also presented. Figure 2 displays the K_{cr} versus DOY relationship for each soil background. Differences in the K_{cr} between the light, dry soil and the dark, wet soil were greater than 40% on DOYs 171 and 176 (LAI of 0.3 and 0.6, respectively). This difference was much greater than reported by Neale (1987).

Huete (1988) presented a technique to minimize soil brightness influences based on red (RED) and near-infrared (NIR) wavelengths. His index is referred to as the soil adjusted vegetation index (SAVI). Although NDVI is defined by

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}, \tag{4}$$

SAVI is defined by

$$\mathrm{SAVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED} + L} \times (1 + L). \tag{5}$$

Comparison of Eqs. (4) and (5) shows that a constant L has been added to the denominator of the NDVI and a multiplication factor $(1 + L)$ has been added to maintain

Table 3. NDVI for Bare Soil and for Effective Cover as Well as the Multiplier and Offset for the K_{cr} Equation [Eq. (1)] for the Various Background Soils

Soil Description	NDVI Bare Soil	NDVI Effective Cover	Multiplier (a)	Offset (b)
Light, dry	0.1111	0.8574	1.0451	0.0339
Light, wet	0.1463	0.8683	1.0803	−0.0080
Dark, dry	0.1826	0.8738	1.1285	−0.0560
Dark, wet	0.2202	0.8773	1.1871	−0.1114

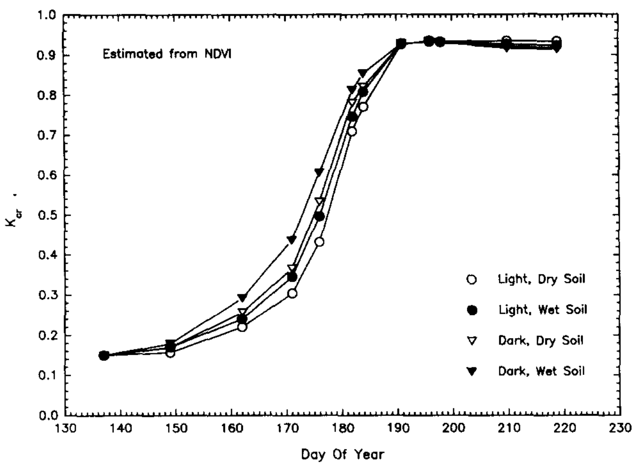


Figure 2. Reflectance-based crop coefficient (K_{cr}) curves for each soil background as estimated from the NDVI.

the bounded conditions of the NDVI, that is, −1 to 1. With $L = 0$, SAVI is identical to NDVI. Based on data collected over grass and cotton, Huete (1988) showed that a value for L of 0.5 reduced soil noise for canopy cover ranging from sparse to dense. Figure 3 shows the seasonal soil background influences on the SAVI with $L = 0.5$. Some differences exist across DOY, but they are minor compared with those for the NDVI (Fig. 1). Dark and light soil data point symbols reverse as the corn crop approached LAI = 1 (around DOY 180) indicating that the SAVI adjustment factor should differ from $L = 0.5$ for denser canopies.

Huete (1988) stated that as the vegetation becomes more dense L becomes smaller in value. He indicated that $L = 1$ for analyzing very low vegetation densities, $L = 0.5$ for intermediate vegetation densities, and $L = 0.25$ for higher densities. An analysis identical to that reported by Huete (1988) was performed on the corn reflectance data for the two extreme soil backgrounds (light, dry and dark, wet) to determine the optimal L for selected DOY data points. The value of L in the SAVI was varied from 0.001 to 10 for each DOY to optimize L as the value where the curves crossed as depicted in Huete's (1988) Figure 3. Table 4 presents the optimized adjustment factor L obtained for the LAI on the selected DOY. Obviously, the optimal adjustment factor was not linearly correlated with LAI as indicated by Huete (1988). Nevertheless, a range of LAI values were associated with three L values; 1) for LAI ≤ 1, $L = 0.6$; 2) for $1 <$ LAI ≤ 2.5, $L = 0.4$; and 3) for LAI > 2.5, $L = 0.15$. Results from optimizing L in the SAVI for LAI are shown in Figure 4. Soil background influences disappear except for minor differences early in the growing season. This suggests that L should be greater than 0.6 for very low LAI; however, the results presented in Table 4 do not support values for $L > 0.6$. Also, SAVI in Figure 4 asymptotes at a higher value than in Figure 3, which is expected since L has a smaller value at that time. The problem with optimizing L for the SAVI is that LAI must be known prior to computing the SAVI.

Baret and Guyot (1991) state that LAI is very difficult to estimate through vegetation index measure-

Table 4. Adjustment Factor L for SAVI Based on Corn LAI with Dark, Wet and Light, Dry Soil Backgrounds

DOY	*LAI*	*L*
149	0.02	0.535
162	0.10	0.560
171	0.31	0.615
176	0.58	0.715
184	1.43	0.390
191	2.58	0.130
196	3.33	0.160

Figure 3. Soil background effects on the soil adjusted vegetation index (SAVI) throughout the vegetative growth period of corn with adjustment factor L set to 0.5.

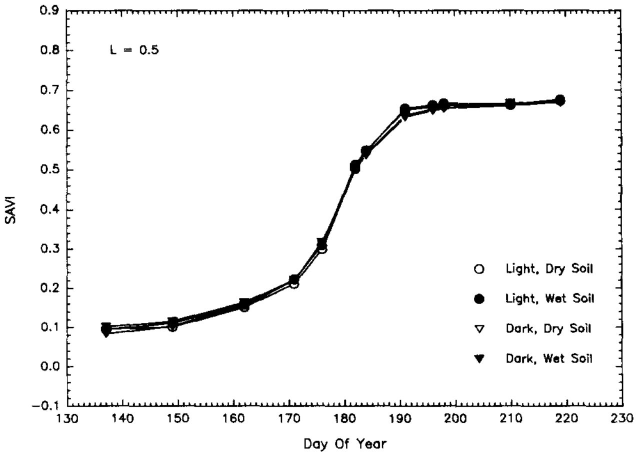
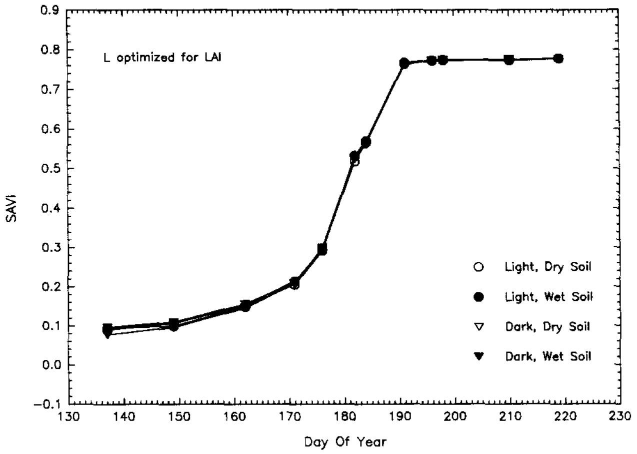


Figure 4. Soil background effects on the soil adjusted vegetation index (SAVI) throughout the vegetative growth period of corn. The adjustment factor L was optimized to the LAI of the crop.



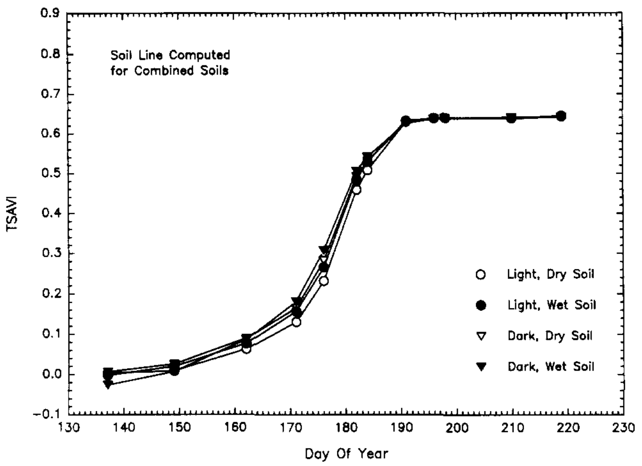


Figure 5. Soil background effects on the transformed soil adjusted vegetation index (TSAVI) throughout the vegetative growth period of corn. Soil line parameters were computed using combined soils.

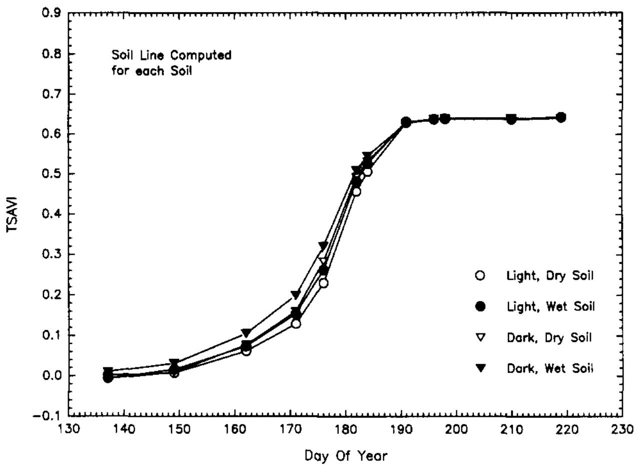


Figure 6. Soil background effects on the transformed soil adjusted vegetation index (TSAVI) throughout the vegetative growth period of corn. Soil line parameters were specific to each soil.

ments, especially when the vegetation index approaches its asymptote or saturation level. They concluded from a comparison of indices that minimize soil brightness influences that their index, the transformed soil adjusted vegetation index (TSAVI), defined by

$$\mathrm{TSAVI} = \frac{c(\mathrm{NIR} - c \times \mathrm{RED} - d)}{c \times \mathrm{NIR} + \mathrm{RED} - cd + 0.08(1 + c^2)}, \tag{6}$$

was best for estimating lower LAI values but was worst at large LAI because it reached its saturation level before other vegetation indices. The TSAVI requires soil line parameters c and d (slope and intercept, respectively) from soil reflectance in the RED and NIR wavebands (TM4 vs. TM3). For $c = 1$ and $d = 0$, TSAVI is equivalent to NDVI. The coefficients for the combined soils were $c = 1.1302$ and $d = 0.0357$. Figure 5 shows the TSAVI for each soil background. TSAVI should equal zero for bare soil. There is definitely greater soil influence differences in TSAVI (Fig. 5) than in the SAVI with $L = 0.5$ (Fig. 3).

Huete et al. (1984) pointed out that increased sensitivity in vegetation assessment can be achieved if soil-specific soil lines are used as a base. Consequently, soil line parameters for the light and dark soils were determined for use with the TSAVI, where, for the light soil, $c = 1.1103$ and $d = 0.0401$ and, for the dark soil, $c = 1.4115$ and $d = 0.0068$. Figure 6 shows the TSAVI result of using soil lines computed for each soil. The data points for bare soil are closer to zero with minor differences among backgrounds; however, more spread exists between the dark, dry and dark, wet backgrounds (Fig. 6) than for the TSAVI using a combined soil line (Fig. 5).

Clevers (1988) presented a simplified reflectance model (designated as Method 1) that corrects the near-infrared reflectance for soil background. Using Clevers' notation, the corrected near-infrared reflectance is calculated as

$$r'_{ir} = r_{ir} - \frac{C_2(r_g r_{v,r} - r_r r_{v,g})}{C_1 r_{v,r} - r_{v,g}}. \tag{7}$$

The technique utilizes canopy reflectance in the green (r_g) and red (r_r) to correct the near-infrared (r_{ir}) based on reflectance at effective plant cover in the green ($r_{v,g}$) and red ($r_{v,r}$) wavebands. The green / red ratio (C_1) and the near-infrared / red ratio (C_2) are derived from soil reflectance. Table 5 presents canopy reflectance in the green and red wavebands at effective plant cover as

Table 5. Green and Red Reflectance of Vegetation[a] in Target Area at Effective Cover and the Soil Reflectance Ratios (Green/Red and Near-IR/Red) for the Various Background Soils

Soil Description	*Green Reflectance* ($r_{v,g}$)	*Red Reflectance* ($r_{v,r}$)	C_1	C_2
Light, dry	0.0564	0.0367	0.7783	1.233
Light, wet	0.0532	0.0331	0.7188	1.324
Dark, dry	0.0518	0.0309	0.7764	1.443
Dark, wet	0.0505	0.0294	0.7770	1.547

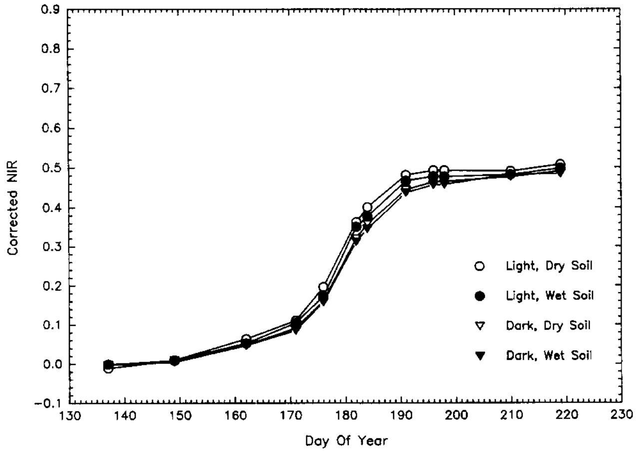
[a] Average values based on data for DOYs 196 and 198.

well as the C_1 and C_2 bare soil reflectance ratios for the various soil backgrounds. The underlying assumption in this model is that there is a constant ratio between the reflectance of bare soil in different spectral bands for a given soil background regardless of soil moisture content and that these ratios can be derived from multiple soil line data and not necessarily from individual soil line data. Soil reflectance at each measurement date for the bare soil ratios as well as green and red reflectance at effective plant cover for the particular soil background were used to calculate the corrected near-infrared reflectance for each background. Results are shown in Figure 7. Corrected near-infrared reflectance was close to zero for bare soil as it should be; however, differences among the four soil backgrounds were more than expected. Use of the bare soil ratios from the combined soils and mean values of effective plant cover reflectance in the green and red wavebands worsened differences among soil backgrounds as the crop developed.

The SAVI with the adjustment factor (L) set at 0.5 and the SAVI with optimized L to LAI were selected for further analysis since these vegetation indices performed best at minimizing soil background influences in the composite crop / soil scene. Data that were acquired over corn with a mobile robotic data acquisition system (Bausch et al., 1990) for several years and at various locaitons were used to evaluate temporal curves of the two selected indices. Vegetation index values from the NDVI were included for curve form comparisons with the two versions of the SAVI since Bausch and Neale (1987) and Neale et al. (1989) showed that the NDVI was similar in shape to Wright's (1982) basal crop coefficient (K_{cb}) curve for corn.

As can be seen in Figure 8, SAVI with $L = 0.5$ is similar in shape to NDVI. The SAVI with optimized L produced a difficult-to-explain transition as L changed from 0.15 back to 0.4 with respect to LAI (DOYs 240–260). Figure 8 was singled out from the other comparisons not shown for two reasons. One, on the NDVI curve, notice that data points 5, 6, 7, and 8 (around DOY 180) do not form a smooth curve because points 5 and 7 were acquired when the soil surface was wet. Points 6 and 8 were acquired with the soil surface essentially dry. Data points 5 and 7 on the SAVI curves are essentially in line with data points 6 and 8, indicating that the index does an excellent job of correcting a wet soil surface. Second, a hail storm occurred on DOY 220 which shredded the upper leaves on the corn plants. The NDVI curve shows little or no indication of such an occurrence after that day, whereas the SAVI curves indicate a reduction in LAI. This analysis suggests that the SAVI with $L = 0.5$ is a likely candidate for use as a reflectance-based crop coefficient. SAVI with optimized L is awkward because LAI must be known to select the appropriate L.

Figure 7. Soil background effects on the corrected near-infrared reflectance throughout the vegetative growth period of corn.



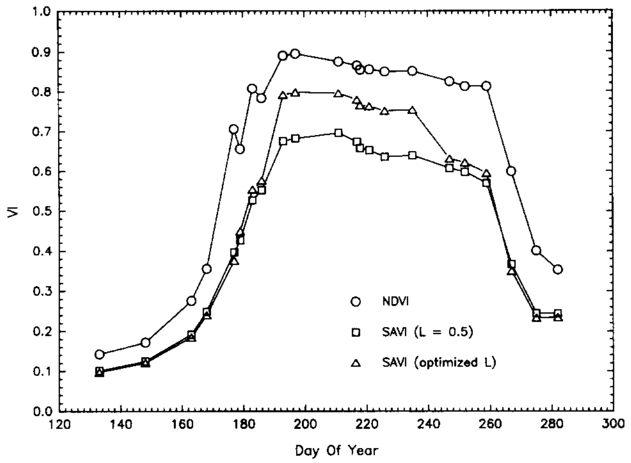


Figure 8. Comparison of selected vegetation indices (SAVI with $L = 0.5$, SAVI with optimized L, and NDVI) calculated from corn canopy reflectance data.

The soil background influences on the SAVI with $L = 0.5$ (Fig. 3) shows that the differences among soil backgrounds were minimal. Consequently, the SAVI was converted into the K_{cr} using the linear scale transformation used by Neale and Bausch (1983) to convert the NDVI into the original reflectance-based crop coefficient. For bare soil, the K_{cb} (Wright, 1982) is 0.15 for corn and the average SAVI for the four soils was 0.094; at effective cover, $K_{cb} = 0.93$ for corn, and the mean SAVI was 0.645. The resulting equation for the reflectance-based crop coefficient is

$$K_{cr} = 1.416 \times \text{SAVI} + 0.017. \quad (8)$$

Figure 9 shows the K_{cr} curves for the four soil backgrounds used in the study. K_{cr} values calculated with Eq. (8) differed by less than 6% between the two extreme soil background conditions (light, dry and dark, wet). This maximum difference occurred at LAI = 0.6

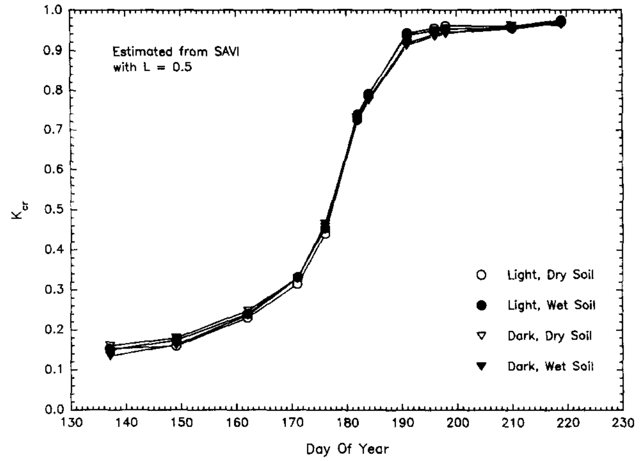


Figure 9. Reflectance-based crop coefficient (K_{cr}) curves for each soil background estimated from SAVI with $L = 0.5$.

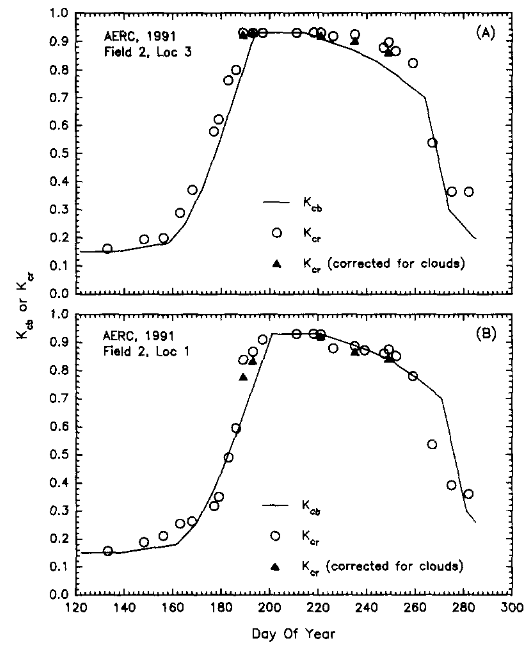


Figure 10. Comparison of the basal crop coefficient (K_{cb}) for corn and the reflectance-based crop coefficient (K_{cr}) based on the SAVI.

(DOY 176), excluding the first data point for bare soil where the difference was almost 12%. Equation (8) should be responsive to all soils whereas K_{cr} based on NDVI (Neale et al., 1989) would not be (Fig. 2, Table 3). Additional calibration of K_{cr} in terms of SAVI should not be required. Since the SAVI did not asymptote (saturate) at effective cover (LAI = 3), K_{cr} will be greater than 0.93 beyond effective cover (LAI > 3). Consequently, when K_{cr} becomes greater than 0.93, it should be capped at that value in order to mimic Wright's (1982) basal crop coefficient curve. Basal crop coefficients for corn presented by Howell et al. (1990) that start at 0.2 and peak at 1.0 (alfalfa reference) or at 1.3 (grass reference) could be scaled as well, depending on the user's preference, to represent the K_{cr}.

Figure 10 compares the K_{cb} curve for corn (Wright, 1982) and the K_{cr} calculated using Eq. (8). This figure represents two locations in the same field where the soil background study was conducted. The K_{cb} was calculated from knowledge of the planting date and the occurrence of effective cover which was determined from leaf area measurements (LAI = 3). This curve is typically developed based on the planting date and an assumed effective cover date to determine drivers for the curve which are percent of time from planting to effective cover and elapsed days after effective cover. A general rule of thumb for estimating the effective cover date for corn is planting date plus 72 days; unfortunately, this assumed date can be off by several days (Bausch and Neale, 1989). The K_{cr} was calculated from reflectance data acquired at a nadir view angle with the mobile data acquisition system (Bausch et al., 1990); no other data or inputs were required.

K_{cr} data in Figure 10A indicate that effective cover occurred sooner than estimated from measured LAI data which was DOY 194. Neale et al. (1989) indicated that effective cover is not necessarily represented by a unique LAI but rather by the fact that a vegetation index typically reaches its maximum value at that time for corn. The first data point represents dry, bare soil; the K_{cr} was 0.16 instead of 0.15 (the expected value). However, K_{cb} values throughout the vegetative growth period were 17.5% low (on the average) with respect to K_{cr} values. Consequently, crop E_t using the K_{cb} data would have been underestimated during vegetative growth and during grain filling as well.

The corn crop represented by Figure 10B essentially stopped growing after DOY 163. The plants had a purplish color which was diagnosed as a phosphorous deficiency; the affected area was subsequently treated with a heavy broadcast application of phosphorous (0-45-0). Rapid growth rates occurred around DOY 177. Effective cover was determined to have occurred on DOY 201 from LAI measurements; however, on DOY 197, under a clear sky, the K_{cr} was 0.91. Thus, effective cover probably occurred somewhat earlier. Again, the first data point represents dry, bare soil; the K_{cr} was 0.155. On DOY 220, hail shredded many of the upper leaves of the corn. K_{cr} data shows this loss of green biomass by the data point on DOY 226 but not on DOY 221. The data in Figure 10A do not show this phenomenon because vegetation density was much greater at that location than in the location represented by Figure 10B.

The SAVI is more susceptible to nonideal sky conditions than the NDVI. Data points in Figures 10A and 10B represented by the filled triangles are best estimates of the K_{cr} for days when data were acquired under variable cloudiness. Reflectance data acquired over a constant target under variable sky conditions on a number of occasions produced the following results: A slight haze in the sky increased the SAVI by less than 1%; however, light, thin clouds created about 2.5% greater values for the SAVI. Cloudy sky conditions with objects on the ground producing faint shadows increased the SAVI by 4% while an overcast sky increased the SAVI by 5–7.5%, depending on cloud thickness and their darkness. Using these results and the observed sky conditions at the time of data collection, the SAVI was decreased by the appropriate percentage and the K_{cr} recalculated. This procedure produced K_{cr} values that were more reasonable than ignoring the sky condition altogether. This is especially true in Figure 10B on DOY 189 (dark, overcast sky) and DOY 193 (cloudy, faint shadows present). The correction on DOY 221 (high, thin clouds) indicated that the hail-damaged upper corn leaves from the storm on DOY 220 were detectable.

CONCLUSIONS

The soil adjusted vegetation index (SAVI) with the adjustment factor L set at 0.5 adquately minimized soil background throughout the growing season. The other indices (TSAVI and the corrected near-infrared reflectance model) did not perform as well. Consequently, the SAVI was selected for transformation into a reflectance-based crop coefficient (K_{cr}) by relating the average value of the SAVI for four soil backgrounds (light to dark soils) to the basal crop coefficient (K_{cb}) for corn at two points on the K_{cb} curve, that is, bare soil and effective cover. The procedure converted the SAVI into K_{cr} values that differed by less than 6% for the two extreme colored soil backgrounds. An equation, $K_{cr} = 1.416 \times \mathrm{SAVI} + 0.017$, was derived that can represent all agricultural soils for estimating the basal crop coefficient for corn and will not require further calibration as does the K_{cr} that is based on the normalized difference vegetation index (NDVI).

Comparisons made between the K_{cb} curve and K_{cr} data for corn showed that the SAVI-based K_{cr} is: 1) independent of the time base parameters (planting and effective cover dates) associated with typical crop coefficients; 2) sensitive to slow and fast plant growth induced by weather anomalies and nutrient deficiencies; and 3) responds to leaf loss caused by hail and probably various forms of plant stress induced by insects, disease, and water deficit (Wiegand and Richardson, 1984). In addition, the K_{cr} corrects for a wet soil surface. The SAVI is more susceptible to sky illumination conditions than the NDVI; however, these irregularities can be corrected. Consequently, the K_{cr} is a true representation of the crop that improves estimated crop E_t so that calculated irrigaiton applications should be similar to the amount of water removed by the crop from the active root zone.

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